

# Long-term Investment Choices for Quinoa Farmers in Puno, Peru: A Real Options Case Study

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## Abstract

The goal of this article is to assess the optimal choices of a smallholder quinoa farmer in the Puno region of Peru, in terms of his decision if and when to undertake certain investments that are expected to increase quinoa yield and crop resistance to harsh weather conditions, such as frost. We focus on two irreversible options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his

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business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of an ancestral cultivation practice that is estimated to offer benefits in terms of yield increase and resistance to harsh climate conditions.

We rely on Real Options Analysis to assess the two types of investment opportunities for the farmer. This approach allows us to determine not only whether the investments should be undertaken or not, but also the optimal timing to do so. We find that one quinoa variety (Kancolla) offers the highest benefits to the farmer and switching to this option should be immediate if investment costs are low; however, as costs increase, the decision to switch quinoa variety is optimally postponed until quinoa price uncertainty is reduced. We find that the Waru Waru option is not worth undertaking unless further evidence related to the increase in the productivity of quinoa is developed. However, at increases in productivity above 20%, the Waru Waru option becomes highly attractive. The article also discusses how quinoa price dynamics, yield sensitivity to frost, and governmental support impact decisions of the smallholder farmer.

Keywords: Quinoa; Smallholder farmers; Real Options; Price and weather uncertainty; Waru waru; Food security; Latin America.

## **Resumen**

El objetivo de este trabajo es evaluar las opciones óptimas del pequeño productor de quínoa (o quinua) en la región de Puno de Perú, es decir, determinar la viabilidad de sus decisiones en términos de si es viable y cuando invertir, a fin de aumenten la producción de quínoa y afrontar de forma efectiva ciertas condiciones climáticas adversas, por ejemplo, las heladas. Nos enfocamos en dos opciones irreversibles, a saber, la gestión de variedades de quinoa y “Waru Waru”. La primera alternativa considera la opción del

agricultor de cambiar de su negocio habitual la variedad de quínoa que acostumbra plantar a otra que tiene otras características de rendimiento y resistencia a las heladas. La segunda alternativa se refiere a la implementación de una práctica milenaria de cultivo que se estima que ofrece beneficios en términos de aumento de rendimiento y resistencia a condiciones climáticas adversas.

Para este propósito nos apoyamos en el Análisis de Opciones Reales (o Real Options Analysis) con el fin de evaluar los dos tipos de oportunidades de inversión con que cuenta el agricultor. Este enfoque nos permite determinar no sólo si las inversiones deben realizarse o no, sino también el momento óptimo para hacerlo. Entre nuestros hallazgos, encontramos que una variedad de quínoa (Kancolla) ofrece los mayores beneficios para el agricultor y el cambio a esta variedad se estima que debería ser inmediato siempre que los costos de inversión que esto implica sean bajos. Sin embargo, a medida que aumentan los costos, la decisión de cambiar la variedad de quínoa a cultivar se postpone de manera óptima hasta que se reduce la incertidumbre del precio de la quínoa. Por otro lado, encontramos que la opción de Waru Waru no vale la pena, a menos que se logre obtener mayor evidencia relacionada con el aumento en la productividad de la quínoa. Sin embargo, esta misma opción se vuelve altamente atractiva en caso de existir aumentos en productividad estimados superiores al 20 %. Este trabajo también explora el impacto que tienen la dinámica de los precios de la quínoa, la sensibilidad al rendimiento de las heladas y el subsidio gubernamental, en las decisiones de inversión del agricultor.

Palabras clave: Quínoa; Quinua; Pequeños productores; Agricultura; Opciones reales; Precio e incertidumbre climática; Waru waru; Seguridad alimentaria; Latinoamérica.

Food security is one of the main topics on the international development agenda

and plays an important role in the achievement of the first two United Nations Sustainable Development Goals UN (2015). Food security is concerned not only with the capacity to produce enough food to feed the world population, but also with the way production is achieved.

Around the world, meat protein is massively grown for human consumption. However, the amount of resources used in the process has significant environmental impacts, including climate change. In this setting, quinoa stands out as an interesting alternative to efficiently produce protein for human consumption, as recently globally popularized by FAO (Ruales and Nair 1992). However, quinoa production has historically prevailed in localized areas of Peru, Bolivia, and Ecuador, and it remains debatable whether massive global production is a viable and sustainable option. In fact, the introduction of quinoa on international markets has been challenging for the local producers, being termed "the food sovereign paradigm" (Avitabile 2015).

Quinoa is mostly produced as a subsistence crop by local farmers in Latin America. Thus, a thorough assessment of quinoa production should consider not only price dynamics and weather processes, but also the possibility of increasing overall production in a steady and sustainable way. The International Year of Quinoa in 2013 proved the potential size of the global demand for quinoa; however, the sharp and sustained drop in prices observed in the years following the event also proved the great threat local producers face when linked to global markets; see Figure 1. This article aims to evaluate two important decisions available for a smallholder quinoa farmer. We focus on two irreversible options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of a traditional cultivation practice that is estimated to offer

benefits in terms of yield increase and resistance to harsh climate conditions.

Our study relies on a Real Options Assessment (ROA) model applied from the perspective of a representative smallholder quinoa farmer. The RAO approach is especially useful for taking decisions under uncertainty. In finance, an option is a title that gives its owner the right, but not the obligation, to buy (in the case of a call option) or to sell (in the case of a put option) another financial title, such as a stock. After the option is exercised (if that becomes optimal ever), there is no return to the previous situation. A real option involves a similar decision, except that the approach is applied to a real life decision rather than to a financial instrument (Chesney et al. 2017). In the context of this article, the representative farmer may choose to invest in a technology that improves the quinoa yield; here, exercising the option means investing in such technology by spending resources to that end; once the investment has been made, the decision is considered irreversible. Moreover, the ROA allows not only for the identification of the decision whether or not to invest, but it helps determine also the optimal time to exercise the option.

Real option models are particularly well-adapted in the context of optimal stopping time problems. They are used in order to check whether decisions should be taken or postponed. The standard tool used in this setting is the Net Present Value (NPV) analysis; however, we decided to use a more flexible tool in order to consider delays in the investment, namely ROA. According to this methodology, an investment should be realized if and only if its NPV, i.e. the difference between its expected discounted payoffs and costs, is positive. The criteria for NPV is then static to the extent to which the choice is between realizing the investment at the date when the NPV is calculated, or never. This is a significant drawback of the NPV criterion. If, instead, investment opportunities are considered as real options, the investor has the right, and not the obligation, to make an investment during a given period of time. When identifying the optimal investment decision, the possibility of

postponing the investment is also taken into account. ROA accounts for the fact that performing an irreversible action at one point in time involves the cost of renouncing the flexibility to wait; if this cost is correctly taken into account in a cost benefit analysis, in order for the action to be economically justified, the benefits from the decision must be higher than in a traditional cost benefit analysis (Chesney et al. 2017).

We employ the ROA approach and calibrate our model to the best available information characteristic for the Arapa District (Puno, Peru). We find that one quinoa variety (Kancolla) offers the highest benefits to the farmer and switching to this option should be immediate if investment costs are low; however, as costs increase, the decision to switch quinoa variety is optimally postponed until quinoa price uncertainty is reduced. We find that the Waru Waru option is not worth undertaking unless further evidence related to the increase in the productivity of quinoa is developed. However, at increases in productivity above 20%, the Waru Waru option becomes highly attractive. The article also discusses how quinoa price dynamics, yield sensitivity to frost, and governmental support impact decisions.

## **The setting of quinoa farming in Peru**

### *Quinoa*

Quinoa or “quinua” is the generic name for *Chenopodium Quinoa*, a crop from the family of the amaranth. It is commonly believed that quinoa is a grain; however, from a botanical perspective, quinoa is a relative of spinach, beets and chard (FAO 2013a). The main world producers of quinoa are Bolivia and Peru. In 2008, the two countries accounted for 92% of the world quinoa production (FAO 2015).

Traditionally, quinoa has been cultivated in a very rudimentary and organic

fashion, since it was first domesticated by the indigenous population in the Andean region around 7,000 years ago FAO (2015). The most popular variety of quinoa worldwide is the white type, produced mainly in the “Sierra” or mountain range of Peru and Bolivia. White quinoa tends to grow in semi-dry areas and is produced in a traditional fashion that usually does not require the use of pesticides. However, most of this production is sold at market price and does not capture the potential benefit of organic certification price premiums.

Depending on the region where the crop is cultivated, there are five general types of quinoa<sup>1</sup> (FAO 2013b): (i) dry valley and humid valley, (ii) altiplano (white and colored), (iii) saltflat, (iv) sea level, and (v) the Yunga agroecological zone and subtropics. Only the first two varieties are cultivated in Peru, while the third and fifth varieties are attributed to Bolivia, while the sea level variety is better adapted to Chile.

This Andean endemic crop is recognized to have important nutritional properties and to have the potential to become an important part of global agriculture, as a main source of protein or a “Super Food.” In fact, the year 2013 was declared by the United Nations “The International Year of Quinoa” or “IYQ”(FAO 2013a). This acknowledgment helped to draw the world’s attention to the role that quinoa could play in providing food security, nutrition and poverty eradication in support of achieving Sustainable Development Goals. The IYQ also allowed for quinoa prices and production to flourish experiencing an atypical increase of between 2012 and 2014 according to official sources. In fact, producer prices increased 139% during the period, while area harvested followed with a corresponding increase of almost 175% (FAO 2017); see Figure 2.

A crop with high nutritional value, quinoa has historically played an important role for low-income inhabitants in Peru and the Andean region in general. In the recent past, quinoa has become a crop of international importance for people at all income

levels and, as a consequence, its production has increased considerably. The trend is expected to continue; Furche et al. (2013) estimate an average annual growth of 22.8% in production for the 1992 - 2012 period.

The increase in quinoa production does not come without environmental side-effects. Jacobsen (2011) warns about the rapid degradation of natural resources due to unsustainable land use for quinoa farming in Bolivia. The observation has been contested in later studies; Winkel et al. (2012) stress that there is no sufficient scientific evidence regarding the rapid social and environmental dynamics in the region, and claim that the report of Jacobsen (2011) misrepresents the situation of quinoa production in southern Bolivia. Data availability for the analysis of social, environmental, and even economic issue in the region remains limited at best.

### *The study location: Puno*

This study focuses on quinoa smallholder farmers in Puno, one of the 24 departments of Peru, formed by 13 provinces in the southeastern area of the country. Puno is located in the western part of the Lake Titicaca, over the Collao Plateau. The Andean mountains make up to 70% of the department's area, and the rest is covered by part of the Amazon rainforest. There are two very distinct regions in the Department of Puno: the plateau or "Altiplano" and the mountain region or "Sierra". Both areas have a cold and dry climate, with a three-to-four month long rain seasons, and a couple months of a very dry season, usually in June and July. As Puno is located in high altitude, it experiences more extreme meteorological conditions than the rest of the country. Soil characteristics tend to be arid or semiarid. Although water is available near the lake area, it is a limiting factor in most of the region. Puno has also been regarded as the cradle of domesticated potato agriculture and is currently is the main producer of quinoa in Peru



Ministerio de Agricultura y Riego (2017).

According to information provided by SENAMHI<sup>2</sup>, there are 44 weather stations located in Puno. However, data from only 5 stations has been cleaned and could be used for analysis at the time of this study<sup>3</sup>; see Figure 2 for a general reference on the location and altitude of the Stations in Puno. The availability of data to be inputted in our model is largely restricted and some of it is not available from local authorities, i.e. Dirección Regional Agraria (2017). Under these conditions, we restricted our analysis to Arapa, whereby both the availability and quality of the data was assessed to be higher.<sup>4</sup>

## Literature Review

This article evaluates agriculture decisions in Latin America. Given the vast importance of this sector for the economy of the region, it is not surprising that most academic research targeting this area focuses on agriculture. Kaufmann and Snell (1997) assesses the sensitivity of corn yield to climatic, social and economic factors. Sietz et al. (2012) identify the patterns of smallholder vulnerability to weather extremes impacting food security in the region. Altieri and Nicholls (2017) focus on the potential role of adaptation and mitigation strategies of climate change for traditional agriculture. They identify the external drivers of vulnerability, and point to the potential of Waru Waru raised fields to reduce such vulnerability. In fact, they describe Waru Waru and similar techniques as *models of climate smart traditional agriculture*. Barrera et al. (2012) study natural resource management in Ecuador and show that the implementation of enhanced management practices contribute to reduced environmental vulnerability and improved welfare. Our article assesses two long-term investment options for quinoa farmers in Puno. We analyze at the option to switch quinoa varieties and the option to invest in the

setup of a Waru Waru agricultural technique. The literature on the latter investment dates quite a while back given the long history of this agricultural approach; however, not many new assessments have been performed in the last decade to update the analysis to present times. Erickson (1986) offers a review of the literature related to raised field practices in agriculture, among which Waru Waru, and provides some information about the potential increases in quinoa yields obtained under Waru Waru compared with the business-as-usual. Mujica Barreda (1997) extends this research and offers a more comprehensive analysis on the profitability of the raised fields in Puno. He specifies the increase in profitability of Waru Waru systems when compared to equivalent fields that do not apply this technology at about 20%. Lhomme and Vacher (2003) highlight the benefits of using the raised fields approach; in particular, Waru Waru is estimated to reduce the effects of night frost. Although their study focuses only on the cultivation of potatoes, it is expected that their findings apply to quinoa as well. Llerena et al. (2004) review 19 articles that describe the physical characteristics of the raised fields in Peru and particularly account for the historical reasons behind the abandonment of these technologies. It is implied in most cases that such abandonment followed particular historic events, such as the elevated mortality in the Indian population in the pre-Columbian era. Llerena et al. (2004). However, not much is clarified regarding the reasons that explain the current low use of the technique in the Andes.

Our article contributes to the literature by developing a dynamic real options model that accounts for market and environmental dimensions of quinoa agriculture in Peru. The concept of option value was introduced in environmental economics since several decades, even before the appearance of real options (Arrow and Fisher 1974; Fisher and Krutilla 1975; Henry 1974). Real Option Assessment is not foreign to Latin America. Numerous studies have been developed to describe different issues within the region; however, the application of this methodology to

agriculture in Latin America, and in particular to Peru, is quite novel. Among the few contributions, an application of ROA in Peru is done by Chesney et al. (2017), whereby the authors focus on REDD (Reducing Emissions from Deforestation and Forest Degradation) projects and aim to identify the optimal deforestation rate and timing to enter the REDD scheme under different risk aversion scenarios.

We rely on ROA to assess two long-term investment options, i.e. quinoa variety management and Waru Waru. One leading goal of the article is to highlight the relevance of relying on ROA models in agriculture. ROA accounts for the flexibility to postpone investment until part of the underlying uncertainty is resolved, offering estimates related to the optimal investment time. The methodology can also be applied to a portfolio of decisions, where several investment options are assessed simultaneously. Another contribution of our model is to incorporate stochastic weather processes into the decision-making process.

## **Long-term investment options in quinoa**

This section provides details on the two agriculture techniques relevant for the quinoa smallholder farmer in Puno. The model to evaluate the two options and the main results are fully described in the following sections.

### *First option: Quinoa variety management*

In the world, there are roughly 120 known seed varieties of Quinoa. Among them, only 13 seed varieties appear to be commercially feasible in Peru (FAO 2015).

Quinoa varieties come in a diverse palette of colors, with white being the best known globally due to the long tradition of its organic cultivation since centuries; red and black varieties are also gaining relevance on some markets. Aside from

color, quinoa varieties come with different levels of yield and resistance to drought or salinity. In fact, according to the survey led by MeteoSwiss, farmers tend to have different preferences for particular quinoa varieties, depending on factors such as tradition, experience, and peer influence. Although many talk about the differences in characteristics of quinoa varieties, very little has been researched to quantify their benefits. Unfortunately, only scarce information exists with regards to differences in agrobotanical and phenological characteristics, the response to biotic and abiotic factors, or the nutritional value of commercial varieties FAO (2015). This gap is unfortunate, as such information could be especially useful for farmers and agricultural entrepreneurs trying to optimize their quinoa production. This is especially true given the fact that there seems to be no incremental cost in producing any specific variety of quinoa, despite the difference in yields and weather resistance.

For the purpose of this study, the management of quinoa varieties was regarded as an independent and exclusive option in which the producer has the opportunity to choose the quinoa variety that optimizes the revenue. Given the data limitations mentioned above, we lead a sensitivity analysis trying to account for a wide range of scenarios.

### *Second option: the Waru Waru technique*

Waru waru is a system of soil management for irrigation purposes and weather mitigation that is believed to have been developed before the rise of the Inca empire in the year 300 B.C. (OAS 2017). Waru Waru is a technique suitable to areas with extreme climatic conditions, such as mountainous areas that experience heavy rainfalls and periodic droughts, and where temperature fluctuations range from intense heat to frost. It is also believed to be very useful in arid and semi-arid areas,

such as the Andean region of Peru and Bolivia (OAS 2017). Despite its expected benefits, the prevalence of the technique remains low. Even more, it appears that even after implementation, Waru Waru has been abandoned in 3 out of 4 projects (Source: Interview with Dr. Alipio Canahua Murillo, April 2017). For the purpose of this study, Waru Waru was regarded as an independent and exclusive option.

### *Other investment options*

In our study the two investment options have been regarded as independent and exclusive. One could argue that the two options should be assessed simultaneously, which could be achieved with the real options approach. However, this would require the estimation of the joint impact of the two options on the revenues of the farmer. Since such correlation has not yet been assessed for these options, the joint evaluation remains out of the scope of the present study, but it could be incorporated in a later stage of the project as information becomes available.

On the same esteem, there are further options that were not included in the current stage of this study such as organic certification, irrigation, technification, climate insurance, use of pesticides, etc. Such options could also result in significant benefits for the producers and could be assessed in a further stage of analysis. Some options, such as irrigation and technification, require that the assessment be led at the community level and not at a farmers level, which would call for a different theoretical model altogether.

Furthermore, important applications of this model could also be implemented for other regions of Peru, including Cuzco, and the costal area. The model could also be applied to obtain further findings in other countries that are also relevant for Quinoa production such as Bolivia and Ecuador. Data for Quinoa in the Andean region seems to be more available for such countries, but it was outside of the scope

of this stage of the study to include them as part of it.

## Model and numerical methods

This section describes the main theoretical setup of our decision-making model that will be solved with the help of the real options approach. We also dig into the main assumptions regarding key model parameters and give details on their calibration.

### *Model setup*

In this article, we take the view of a smallholder quinoa farmer in the Peruvian altiplano that is considering several investment options that could increase his overall profits. The two long-term decisions he is evaluating are (i) changes in quinoa variety and (ii) the Waru Waru farming technique, as described in Section . The two options<sup>5</sup> consist in very different farming options, the evaluation of their feasibility calls for a fairly similar decision process. Namely, we assume that the representative quinoa farmer is a rational decision maker who will choose to invest if and only if the investment will increase the expected sum of future discounted yearly profits compared to the business-as-usual. We assume that the investment horizon of the farmer is  $[0; T]$ ; in our numerical solution, we consider  $T = 20$  years and a discount rate of 9%.

Under the business-as-usual, where no long-term investment option has been implemented so far, the yearly profit of the farmer will be given by:

$$\pi_t^{BaU} = P_t q_t(W_t) - C(q_t) \quad (1)$$

Equation 1 describes the factors that influence the current yearly profit of the farmer, where  $P_t$  is the year  $t$  price of quinoa.  $q_t$  is the quantity the farmer harvests

at the end of the planting season. As described below, we allow  $q_t$  to be a function of weather conditions ( $W_t$ ).  $C(\cdot)$  is the cost production function that depends on the quantity produced that year ( $q_t$ ). Without loss of generality, we assume one hectare of land; thus the quantity harvested  $q_t$  is measured in tons of quinoa per hectare.<sup>6</sup> Quinoa is a highly robust crop with high tolerance for weather variations compared to other crops. However, the plantation of quinoa is not totally immune to weather conditions. In fact, the survey administered to farmers in Puno highlights that the conditions that are of highest concern for quinoa farmers are above all frost, followed by drought and hail. We thus opt here for modelling the quantity of quinoa harvested as a function of frost events, as described below.

To increase their yearly yield and reduce the vulnerability of quinoa production to weather conditions, the quinoa farmer has a set of long-term investment options he can undertake. In our model, if the farmer undertakes an investment ( $A$ ), his yearly profit would be modified and given by:

$$\pi_t^A = P_t q_t(W_t, A) - C(q_t, A) \quad (2)$$

where  $P_t$  is the time  $t$  price of quinoa,  $q_t$  is the quantity harvested depending on both weather conditions ( $W_t$ ) and the long-term adaptation option that has been already implemented ( $A$ ), and  $C$  is the cost production function that depends on the quantity produced and the adaptation options already implemented by the farmer. Consider now that the farmer is evaluating the option to undertake a long-term investment in the future. The expected total revenue of the farmer is given by the sum of yearly profits under the business-as-usual and under the new regime after the investment has been made:

$$\Pi = \mathbb{E} \left[ \sum_{t=0}^{\tau_A} e^{-rt} \pi_t^{BaU} - IC_{\tau_A} e^{-r\tau_A} + \sum_{t=\tau_A}^T e^{-rt} \pi_t^A \right] \quad (3)$$

where  $IC_{\tau_A}$  is the one-time sunk cost the farmer incurs with the investment in option  $A$ . In Eq. 3,  $\tau_A$  marks the time of the investment. Formally,  $\tau_A$  is a stopping time, whereby the farmer moves from the business-as-usual regime to the post-investment one. Let  $(\Omega, F, \{F_t\}_{t \in I}, \mathbb{P})$  be a filtered probability space, i.e. a probability space equipped with a filtration of  $\sigma$ -algebras. Then the random variable  $\tau_A$  is a stopping time if  $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$ , i.e. the decision to stop waiting and to invest is only based on historical data.

The farmer will decide when to invest in the adaptation option by maximizing his total expected future profits:

$$\max_{\tau_A} \Pi \tag{4}$$

### *Assumptions regarding the model variables*

#### *The price of quinoa*

One important model variable is the price of quinoa and its evolution over time. To represent the price dynamics, we rely on the historical distribution of quinoa prices received by the farmer in the Arapa region. Figure 3 below captures the historical quinoa price evolution. While for a long time quinoa prices have been stable at a low level per kilogram (until 2008), with the international increase in the demand for quinoa, prices have experienced severe shocks over the last decade.<sup>7</sup> Based on these historical observations, we suggest to model the quinoa price with the help of a random variable represented by a trinomial tree. Namely, each year the quinoa price received by the producer can (i) remain at the level of the previous year with probability  $p_1 = 0.1579$ , (ii) increase by 20.28% relative to the previous year with probability  $p_2 = 0.4737$ , or (iii) decrease by 28.37% percentage points relative to the previous year with probability  $p_3 = 0.3684$ , where all price movements and associated probabilities have been calibrated on historical data.<sup>8</sup>



### *Weather conditions impacting the harvest of quinoa*

Among the weather phenomena impacting quinoa production, we choose to focus on agronomic frost (defined as temperatures at and below  $-4^{\circ}\text{C}$ ), as it is the event farmers seem to be mostly concerned with based on the information gathered in the individual surveys. The number of yearly occurrences of days with frost during the harvest season (September - May) can be modeled as a random independent variable. We rely on historical data to estimate the distribution of the number of frost days during the harvest season. Fig. 4 below captures the evolution of frost days in a harvest year in Arapa (Puno).

The historical frequency of the number of frost days impacting the total quantity of quinoa harvested in a year is captured in Table 1.

Let us define  $W_t \in [0; 30]$  as the number of days events randomly taking place during the planting season.<sup>9</sup> Table 1 captures the observed historical probability of the number of frost days. Assuming an unchanged distribution over time, these probabilities will be used in our model to form expectations about the number of frost days to be expected during the planting season each year.

### *Estimating the impact of frost on the harvest of quinoa*

Quinoa production is sensitive to negative temperatures. Analyzing historical data, we observe a negative correlation (-0.14) between the number of days with frost during the planting season and quinoa production.<sup>10</sup>

To find out the relation between the number of yearly frost days and quinoa production, we run the following univariate regression:

$$q_t = \alpha + \beta W_t + \epsilon \quad (5)$$

Fitting Eq. 5 on historical data proved to be a very challenging task due to very

poor data quality available for the region of interest. Faced with this uncertainty, we chose to run the model for a set of benchmark assumptions and then lead a sensitivity analysis around these values. We set  $\alpha$  equal to the average annual quinoa production per hectare (expressed in kilograms per hectare) and  $\beta = -2$  for the business-as-usual scenario.

Equation 5 captures how the quantity of quinoa harvested in year  $t$  is affected by frost. The computed expression is used to complete the definition of yearly profits in Eq. 1.

## Results and Sensitivity Analysis

This section presents the results for the optimal times to invest in the long-term adaptation options that are expected to increase the total revenue of quinoa small farmers.

All models have been calibrated for the Arapa region in Puno. The analysis also focuses on the way the results change when varying important model parameters, in particular governmental subsidies for implementation, sensitivity of quinoa production to frost, and movements in quinoa prices. The decision horizon of the quinoa farmer is assumed to spread over 20 years. Therefore, whenever the model shows that the optimal switching time is 20, it should be interpreted that the option to invest is not actually optimal for the entire decision horizon of the farmer.

Whenever the expected optimal stopping time is 1, it should be interpreted that the farmer is expected to invest in the following year, as implementation is assumed to require some time.

### *First option: Crop Management*

In this section we present the results regarding the optimal time to switch from a business-as-usual quinoa variety to a different one. Quinoa varieties have different characteristics, in particular in terms of production yield (kilograms per hectare) and crop resistance to frost. Depending on the underlying characteristics, it might be beneficial for the farmer to abandon the quinoa variety he is usually planting in favor of a different one. The real option approach allows us to assess not only whether such a switch would make economic sense, but also to determine the optimal time to do so.

We focus our analysis on three quinoa varieties typical for the altiplano in the Puno region. The three varieties are Illpa, Salcedo, and Kancolla, and they have been identified as the most prevalent in the region by the quinoa farmers in the survey led by Senahmi and MeteoSwiss in December 2016 and also by their commercial relevance as described in the Catalogue of Commercial Varieties of Quinoa in Peru FAO (2015).

Table 2 captures the production characteristics of the three quinoa varieties considered, as well as the source where the information was gathered from. In the benchmark scenario, we assume that the sensitivity to frost is the same for all quinoa varieties, and we relax this assumption in the sensitivity analysis later on. As well, under the standard set of assumptions, the model fixes the cost of switching from one quinoa variety to another at 10% of the quinoa revenue in the year the switch takes place. This assumption is relaxed later on.

Table 3 captures the main results when the option to switch from the business-as-usual quinoa variety to a different one is considered. As each of the three quinoa varieties represents the status quo for some of the representative farmers in the Puno region, we run the analysis for all combinations of varieties.

The purpose is to comprehensively assess the benefits of transiting from each quinoa variety to each alternative variety. The model reveals that, under the benchmark assumptions, the Kancolla variety dominates the Illpa and Salcedo varieties. Otherwise stated, farmers who currently plant either Illpa or Salcedo quinoa varieties would benefit from switching right away to the Kancolla one, as this would increase their total revenues. The result is reflective of the fact that Kancolla has a higher yield per hectare than the other two varieties considered, while the other characteristics are held constant.

#### *Sensitivity to the cost of switching quinoa varieties*

Under the benchmark case, we showed that the Kancolla variety is the most profitable one and, consequently, farmers should consider adopting it as soon as possible. However, this result holds as long as switching costs do not surpass the benefits of the change. The cost of switching from one quinoa variety to another was assumed to amount to 10% of the total revenue in the year the switch takes place. In this section, we relax this assumption and check whether and when it is optimal to switch to Kancolla, given a large range of switching costs.

Figure 5 illustrates the results for the optimal switching time from the Salcedo to the Kancolla quinoa varieties at different levels of the switching cost. The results capture a very high sensitivity of the decision to switch to the level of cost.

Incurring a cost of 16% of the year's revenues delays the decision to switch by fifteen years; a further percentage increase in cost renders the option to switch worthless. This high sensitivity to the switch cost is reflective of the fact that switching quinoa varieties from Salcedo to Kancolla results in only modest increases in total revenues that can be easily swiped away when the change is costly.

### *Sensitivity to frost resistance*

Our results so far have revealed that the Illpa variety is the least profitable one and the farmers who currently cultivate it would be better off by adopting either the Salcedo or Kancolla varieties as soon as possible. This result is based on the lower yield per hectare attained by Illpa compared to the other two, all other conditions equal. However, there is high uncertainty regarding the ability of the different quinoa varieties to resist to frost. In this section, we explore whether a higher frost resistance of Illpa compared to the other two quinoa varieties would render it more profitable in the aggregate and, therefore, a good option to switch to.<sup>11</sup>

Figure 6 shows the optimal time to switch from Illpa to either Salcedo or Kancolla varieties, when the resistance of Illpa is held at the benchmark level ( $\beta = -2$ ) and the resistance to frost of the other two varieties is allowed to take values between  $-2$  and  $-10$ . It is striking that under the considered scenarios, it is never optimal to postpone the decision to switch from Illpa to the other two varieties, no matter the level of resistance to frost. This result is important in that it highlights the reduced role that the resistance to frost has in comparison to the long-term trend in quinoa yield.

For completeness, we also run the model for the situation in which the sensitivity to frost of Salcedo and Kancolla is kept at the benchmark level ( $\beta = -2$ ), while that of Illpa is assumed to be very low ( $\beta = -1$ ). Table 4 confirms that even under this scenario, the farmer is better off switching to the Salcedo or Kancolla varieties, as this would increase the farmer's total profits.

#### *0.1. Second option: Waru Waru*

In this section, the analysis is focused on the farmer's option to invest in the implementation and maintenance of the Waru Waru farming technique. Although

fairly expensive, this long-term investment decision is expected to bring important benefits in terms of increase in quinoa yield and reduction in the crop's sensitivity to frost. However, the research on the exact magnitude of these benefits remains scarce, leaving a high uncertainty regarding the parameters the yield ( $\alpha$ ) and frost sensitivity ( $\beta$ ) parameters. Our review of the existing literature leads us to the decision to consider a benchmark case where the sensitivity of quinoa to frost under a Waru Waru regime is kept at the same level as under the business-as-usual, while the increase in quinoa yield per hectare is 20% higher under Waru Waru than under business-as-usual. These assumptions are relaxed further on.

Our model finds that, under the benchmark assumptions, the implementation and maintenance costs needed to ensure a good functioning of the Waru Waru system are prohibitively high and it is never optimal for the farmer to invest in this option. The following sections illustrate how this result changes when we vary the assumptions regarding the key parameters.

#### *Quinoa price and sensitivity to frost*

We first analyze the scenario in which the market for quinoa becomes stronger over time and this increase in market maturity is reflected in prices that tend to increase on average over time, and experience only limited down movements. The idea behind this analysis is to be able to pinpoint whether better quinoa prices would overcome the high implementation costs and render Waru Waru a viable option. Fig. 7 below illustrates the optimal time the farmer is expected to invest in the Waru Waru option when the magnitude in the down movement in prices is allowed to vary, all other conditions constant. We find that, under all considered scenarios, the Waru Waru option remains infeasible, as even always increasing quinoa prices (magnitude of down movement = 0) are not sufficient to justify the high Waru Waru

investment cost.

As mentioned above, one of the advantages of the Waru Waru technique is that it decreases the sensitivity of quinoa to frost events and, thus, guarantees better yields in years with many or severe frost events. Fig. 8 captures the results for the optimal decision to invest in Waru Waru when the sensitivity of production to frost under Waru Waru is allowed to be lower than under the business-as-usual. We find that, despite helping achieve a much lower sensitivity to frost, the implementation cost of Waru Waru is still too high compared to the potentially increased revenues. Even when the sensitivity to frost under Waru Waru is completely wiped out ( $\beta = 0$ ), the farmer would be better off under the business-as-usual. As in the case of the first option, i.e. switching the quinoa variety, the role played by the resistance to frost parameter seems limited.

#### *Governmental subsidies and increases in productivity*

The previous section has shown that the current estimates regarding the implementation and maintenance costs of the Waru Waru technique are too high for the quinoa farmer and it appears optimal for him to remain under the business-as-usual scenario. In this section we test the robustness of this result by further relaxing the assumptions related to some key model parameters.

First, we are interested in understanding whether some governmental support, in the form of subsidies for Waru Waru implementation, would increase the value of the Waru Waru option and by how much. Fig. 11 illustrates the sensitivity of the optimal investment time in Waru Waru at different levels of governmental support. We find that only an almost full (above 80%) subsidy of the implementation cost would render the Waru Waru option interesting for the farmer. The results seem to be highly sensitive to the level of subsidy in this high range, where increasing the subsidy from 90% to 100% would lead the farmer to optimally expedite the

investment decision from year 18 to the present year.

Although high governmental subsidies could become feasible in a world where Peru aims to establish itself as a world leader in quinoa production, it remains unlikely that subsidy levels took such high values to render the investment in Waru Waru optimal right away.

Next, we analyze the attractiveness of the Waru Waru option for different levels of increases in productivity compared to the business as usual. The uncertainty for the effect of Waru Waru on quinoa productivity is high and we, thus, consider a broad array of values. As a brief comparison, it has been estimated that the increase of potato production under Waru Waru is 40% higher than under the business-as-usual (Mujica Barreda 1997). We find that, indeed, the impact of the Waru Waru technique on quinoa productivity plays a major role in the decision to adopt quinoa; see Fig. 9. At an increase in the productivity of quinoa of 40% under Waru Waru, the option to invest in this technique is optimal in year 12 of the investment horizon. The results are highly sensitive to increases in productivity above the 40% level, such that at 60% an imminent investment in Waru Waru would be optimal.<sup>12</sup>

Having discovered the paramount role that the increase in productivity under Waru Waru plays for the feasibility of this investment option, we revisit the role of governmental subsidies. Fig. 10 captures the results for the optimal investment times when both the increase in productivity under Waru Waru and the level of government subsidies are allowed to vary. We find that even a modest support from the government (subsidy of 10%) would trigger a fast investment in Waru Waru at increases in productivity above 30%. The results are even more striking for higher subsidies.

Our results signal the importance of leading further investigations regarding the capacity of Waru Waru to increase quinoa yield. Once the uncertainty regarding



this parameter is lowered, clear recommendations could be formulated regarding the optimal timing for the farmers to adopt this option. The potential role of the government in supporting regional development appears to depend on this key parameter as well.

## Conclusion

This article focuses on the decisions a smallholder quinoa farmer in the Peruvian altiplano faces in order to increase his profits. We rely on a Real Options approach that accounts for uncertainty in future quinoa prices and weather events that impact the yearly quinoa yield. The Real Options approach is a technique that, similar to NPV, assists a rational decision-maker in evaluating an investment decision. However, contrary to the NPV approach, Real Options allow for more flexibility in the decision-making process and account for the possibility to postpone an irreversible decision until more information is gathered regarding the stochastic variables.

In this article, we have evaluated two long-term investment options, namely (i) quinoa variety management and (ii) the Waru Waru farming technique. Regarding the first option, our results show that, depending on the current quinoa variety, switching to a different one might be optimal immediately, as better varieties exist that are suitable for the Altiplano and provide higher yields and consequently larger profits. In particular, the Kancolla variety has the highest yield and should be considered right away by quinoa farmers that are currently relying on the Illpa or Salcedo varieties. However, we also show that the decision to adopt new quinoa varieties is highly sensitive to the cost incurred when the switch is made, be it the cost of new seeds or of learning how to handle this new variety. Our results also show that the sensitivity to frost of the different quinoa varieties remains a factor

with low power to influence the investment decision. Investment decision is based only in the results of the assessment and does not include any personal preference or traditional values of the farmer.

Regarding the second option, we find that investing in Waru Waru is prohibitively expensive for the quinoa farmer, under benchmark assumptions. However, a few factors seem to play a crucial role in the optimality of the investment decision.

Importantly, it has been estimated that the Waru Waru technique increases the yearly quinoa yield, by so much as 40% for potatoes. The estimates for the impact of Waru Waru on quinoa production lack scientific evidence, leaving room for high uncertainty around this key feature. Our study further puts emphasis on the importance of solving this uncertainty, as our results show that for productivity increases above 20% the quinoa farmer is expected invest in the Waru Waru option in the medium-term future, and at increases above 50% the investment should be immediate. One needs to be cautious when interpreting these results, as high uncertainty remains regarding the actual productivity increase due to Waru Waru.

We also analyze the role that governmental support could play for the development of the quinoa market through incentives at the smallholder level. We find that governmental subsidies for the implementation of Waru Waru could play a significant role in bringing the optimal investment time closer to the present, especially at increases in productivity above 20% compared to the business-as-usual.

Our study made best attempts to lead an accurate analysis and formulate clearcut results that could be relevant for practitioners, policymakers, NGOs, and other stakeholders. However, we also tried to emphasize throughout our report the high uncertainty surrounding many of the key parameters of the analysis. Our results should therefore be interpreted with great care and adapted to the specificities of the context of interest. It is also important to acknowledge that, although the results

are sensitive to assumptions, the methodological approach embraced in this study is robust and can be applied to a variety of contexts. Further investment options and different geographic regions could easily be accommodated in a future study.

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## Notes

<sup>1</sup>This five general Quinoa types are not to be confused to the specific seed varieties described in the Section "Longterm investment options in quinoa" of this article.

<sup>2</sup>Servicio Nacional de Meteorología e Hidrología del Perú.

<sup>3</sup>These are Desaguedero in the South, Lampa, Puno and Pampahuta in the central part, Arapa, Progreso and Chuquibambilla in the North.

<sup>4</sup>Some other stations, such as Pampahuta, were regarded to be too high in elevation (over 4300 meter above sea level) and resulted to be irrelevant for the study.

<sup>5</sup>Although the two options are equivalent to an investment decision, we recognize that the farmer does not necessarily fund them directly as he can get partial or complete direct funding from third parties, i.e. the government, NGOs, etc.

<sup>6</sup>The results of the survey of quinoa farmers in Puno reveals that the average plot size sowed with quinoa was of 0.47 hectares during the 2015/2016 harvest.

<sup>7</sup>2014 has been named the "International Year of Quinoa" and governmental support for quinoa promotion has boosted the price of quinoa to almost ten times its historical average. Prices have since fallen dramatically but fluctuate above the long-term mean.

<sup>8</sup>The probabilities and respective percentage moves have been estimated based on the historical distribution of the quinoa price received by the producer in Arapa. A historical price change in the range [-1%;1%] has been considered insignificant and therefore counted as a zero change in price. The percentage changes have been computed as averages of upward and downward moves.

<sup>9</sup>The historical data available for Arapa includes only one registered event that had more than 7 days of frost during the quinoa planting season in the period 1996 - 2014. Namely, in the quinoa season 2000 - 2001, 26 days of frost have been registered.

<sup>10</sup>The coefficients have been calibrated for Arapa in the Peruvian Altiplano over the period 1996 - 2012, based on yearly observations.

<sup>11</sup>For the purpose of this study, the estimated optimal investment decision is based on maximizing total expected profits and does not include the personal preferences or traditional values of the farmer. In reality, the choice of quinoa variety can be influenced also by the farmers' past experience, choices of the peers, and even NGOs or local governments.

<sup>12</sup>The values considered by our study for the increase in productivity due to Waru Waru are only illustrative; further research could bring evidence for or against some particular values.

## Tables

Table 1: Number of Yearly Frost Days and Associated Historical Probability during the Quinoa Planting Season (September - May).

Number of frost days	Historical probability
0	0.2778
1	0.0556
2	0.1667
3	0.1667
4	0.0556
5	0.0556
6	0.0556
7	0.1111
> 7	0.0556

Source: Own illustration based on data from SENAMHI (2017)



Table 2: Production Characteristics of Three Quinoa Varieties Typical for Altiplano.

Variety	Yield (kg/ha, Alpha in Eq. 5)	Time to physiological maturity (days)	Production cost (USD/kg)	Sensitivity to frost (Beta in Eq. 5)
<b>Illpa</b>	1,672	130.3	0.1038	-2
<b>Salcedo</b>	1,906	129.5	0.1038	-2
<b>Kancolla</b>	1,929	133.6	0.1038	-2
Source	Bertero et al. (2004)	Bertero et al. (2004)	Mujica Barreda (1997)	Own

Table 3: Expected Optimal Time to Switch Quinoa Varieties under Benchmark Assumptions.

Switch from	Switch to		
	<b>Illpa</b>	<b>Salcedo</b>	<b>Kancolla</b>
<b>Illpa</b>	-	1	1
<b>Salcedo</b>	20	-	1
<b>Kancolla</b>	20	20	-

Table 4: Expected Optimal Time to Change Quinoa Varieties when the Resistance to Frost of the Illpa variety is -1 and for Salcedo and Kancolla is -2.

Switch from	Switch to		
	<b>Illpa</b>	<b>Salcedo</b>	<b>Kancolla</b>
<b>Illpa</b>	-	1	1
<b>Salcedo</b>	20	-	1
<b>Kancolla</b>	20	20	-

## Figure Captions

Fig. 1. Official Price of Quinoa in USD per Hectare as reported by FAO

Fig. 2. General location of weather stations in Puno

Fig. 3. Historical evolution of the price of quinoa as received by the producer in Arapa (Puno). Source: Own illustration based on data from INEI (2017).

Fig. 4. Historical evolution of the number of frost days in Arapa. Source: Own illustration based on data from SENAMHI (2017)

Fig. 5. Expected optimal switching time from the Salcedo quinoa variety to the Kancolla one at different levels of switching cost.

Fig. 6. Expected optimal switching time from the Illpa quinoa variety to the Salcedo one at different levels of sensitivity to frost of Salcedo.

Fig. 7. Expected optimal investment times in Waru Waru at different quinoa price changes.

Fig. 8. Expected optimal investment times in Waru Waru at different sensitivity levels to frost.

Fig. 9. Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs.

Fig. 10. Expected optimal investment times in Waru Waru at different levels of productivity increases.

Fig. 11. Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs and of productivity increases.

## Figures

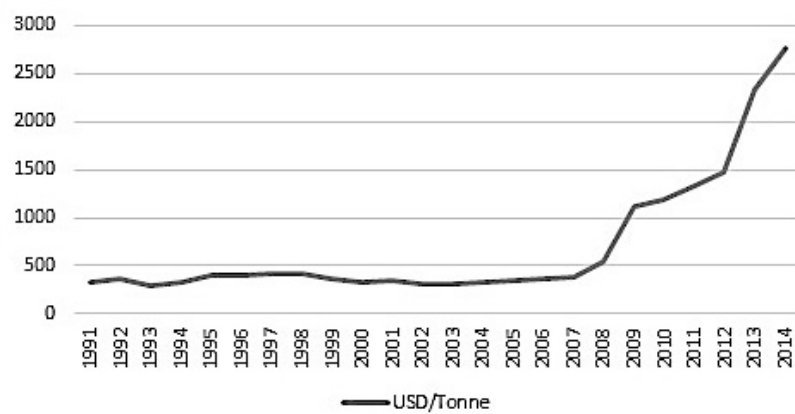


Fig. 1: Official Price of Quinoa in USD per Hectare as reported by FAO  
FAO (2017)

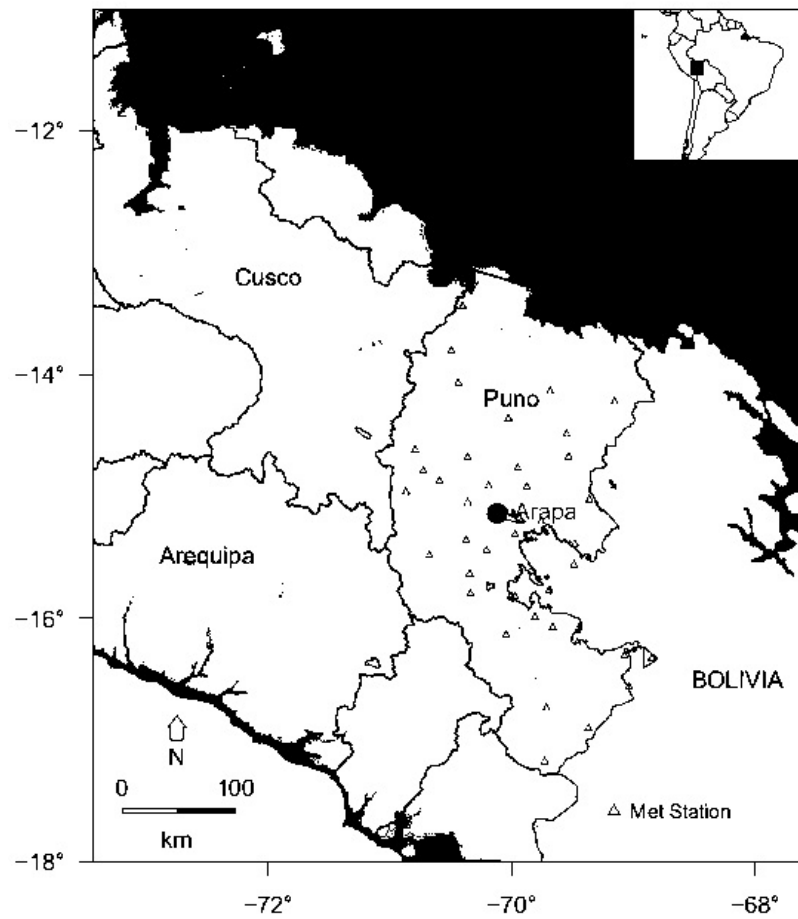


Fig. 2: General location of weather stations in Puno  
SENAMHI (2017)

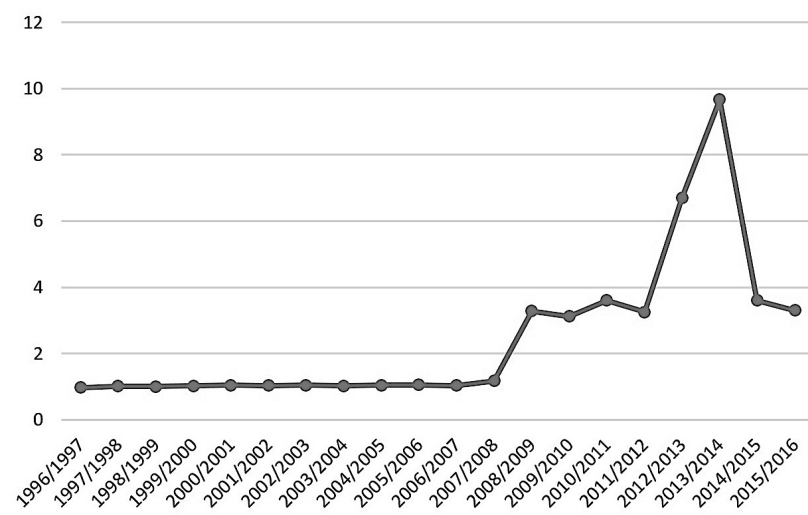


Fig. 3: Historical evolution of the price of quinoa as received by the producer in Arapa (Puno). Source: Own illustration based on data from INEI (2017).

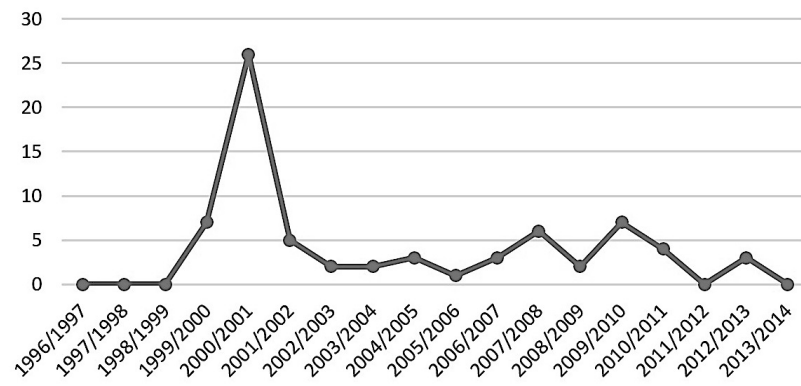


Fig. 4: Historical evolution of the number of frost days in Arapa. Source: Own illustration based on data from SENAMHI (2017)



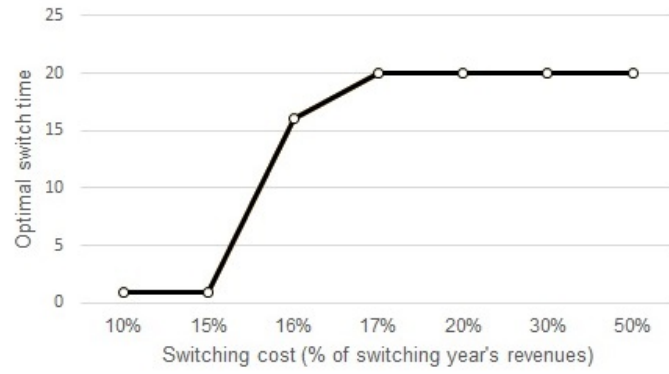


Fig. 5: Expected optimal switching time from the Salcedo quinoa variety to the Kancolla one at different levels of switching cost.

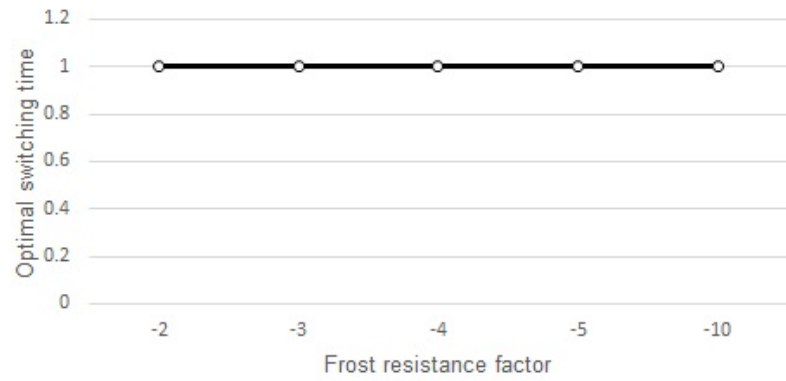


Fig. 6: Expected optimal switching time from the Illpa quinoa variety to the Salcedo one at different levels of sensitivity to frost of Salcedo.

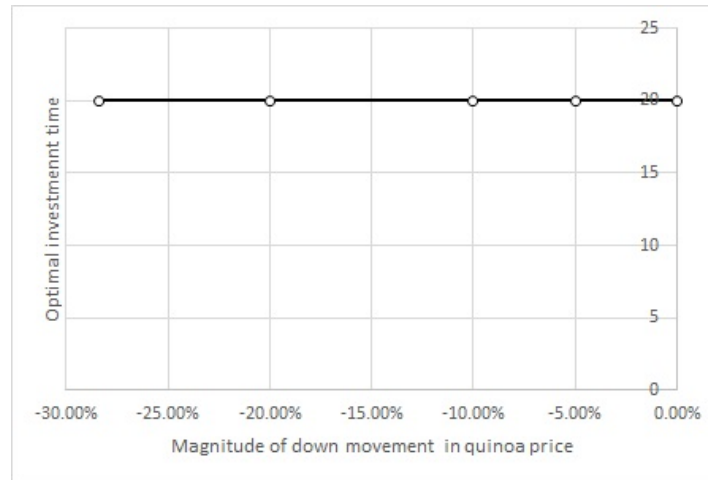


Fig. 7: Expected optimal investment times in Waru Waru at different quinoa price changes.

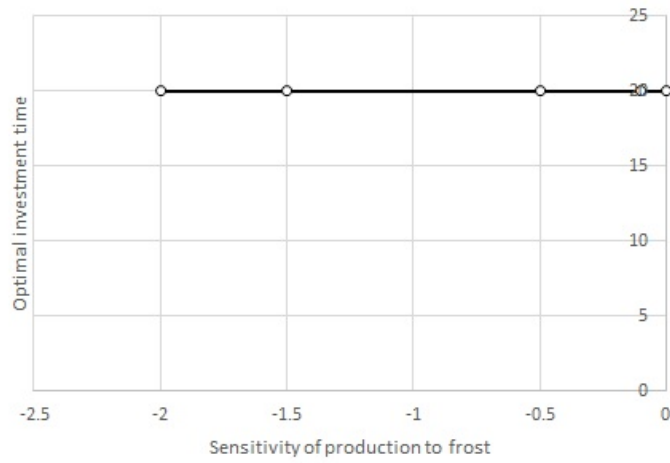


Fig. 8: Expected optimal investment times in Waru Waru at different sensitivity levels to frost.

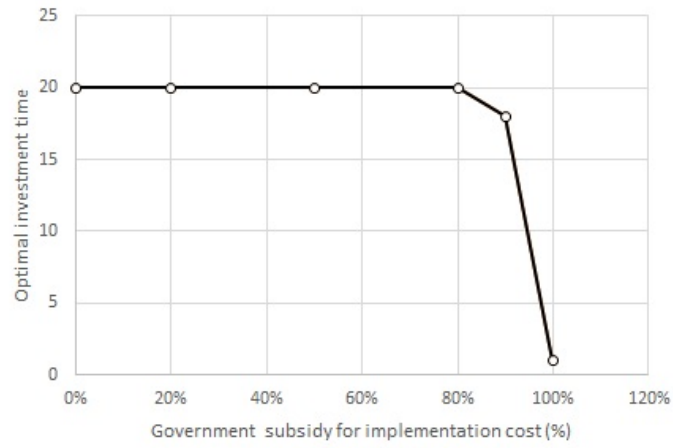


Fig. 9: Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs.

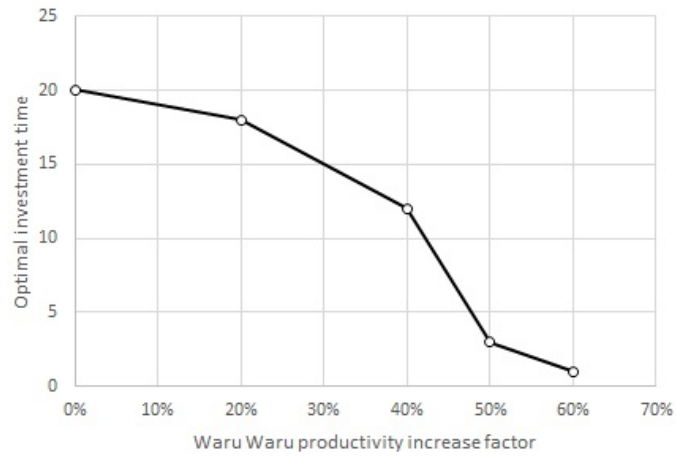


Fig. 10: Expected optimal investment times in Waru Waru at different levels of productivity increases.

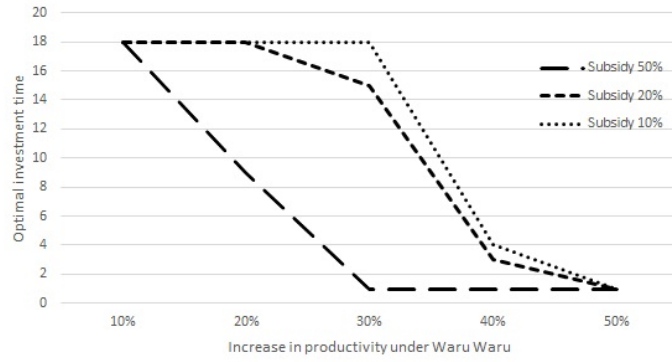


Fig. 11: Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs and of productivity increases.